Space Rider - Developing ESA's Autonomous Space Vehicle Capability

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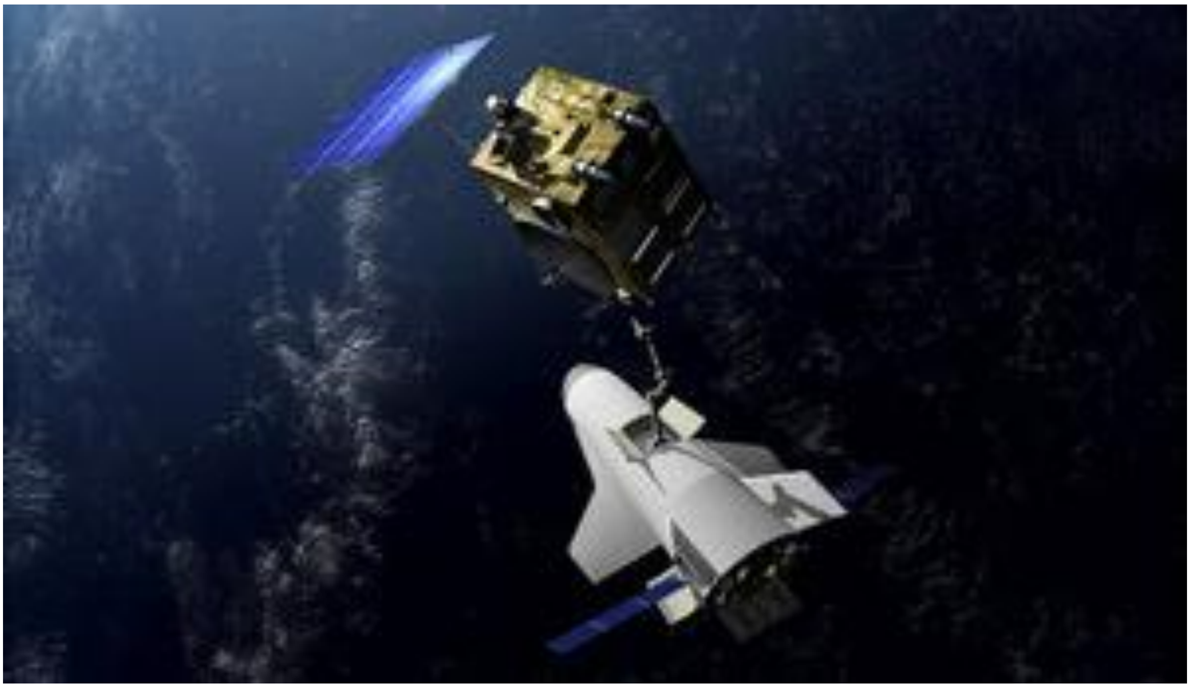


Abstract

The ever increasing demand to access Low Earth Orbit (LEO) has prompted a recently renewed global interest in Launch Vehicle (LV) and Space Vehicle (SV) development. The primary aim of new designs has been to reduce the cost of accessing space, often by maximising vehicle reusability. Despite recent test and demonstration successes, the maturity of the European Space Agency's (ESA's) reusable LV and SV technology is still considered to be below that of major space fairing nations; the United States, Russia and China. To address this knowledge gap and maintain pace with the rest of the world, ESA have been developing an autonomous and reusable SV capability known as Space Rider.

Initially this paper discusses why an agency or nation may want to develop an autonomous SV and goes on to present an overview of SVs, both past and present. ESA's SV development with its Space Rider programme and preceding demonstrator, the Programme for Reusable In-orbit Demonstrator for Europe - Intermediate eXperimental Vehicle (PRIDE IXV), are then introduced. Following this, an overview is given as to how Lockheed Martin UK – Ampthill (LMUK Ampthill) have been contributing to the development of three critical Space Rider subsystems; the Aerodynamic Surface Control System (ASCS), Landing Gear and Mid-Air Retrieval (MAR) system. Key design drivers and trade-offs are highlighted to illustrate some of the engineering challenges associated with developing an autonomous SV. Finally it is shown how SV operators can realise a large cost saving by using MAR instead of conventional Landing Gear.

Acronyms

ACU	Actuator Control Unit
AMG	Aero-Manoeuvring Grapple
ASCS	Aerodynamic Surface Control System
COPUOS	Committee on the Peaceful Uses of Outer Space
EMA	Electro-Mechanical Actuators
ESA	European Space Agency
HBW	Hook-Boom-Winch
IRAD	Internal Research and Development
ISS	International Space Station
IXV	Intermediate eXperimental Vehicle
LEO	Low Earth Orbit
LMSSC	Lockheed Martin Space Systems Corporation
LMUK	Lockheed Martin UK
LV	Launch Vehicle
MAR	Mid-Air Retrieval
NASA	National Aeronautics and Space Administrator
OBC	On-Board Computer
PRIDE	Programme for Reusable In-orbit Demonstrator for Europe
RAeS	Royal Aeronautical Society
SSTO	Single-Stage-To-Orbit
SV	Space Vehicle
TLC	Trailing-Line-Capture
TPS	Thermal Protection Systems
TRL	Technology Readiness Level
UN	United Nations
USAF	United States Air Force

Introduction – Why Build a Space Vehicle?

Since the early 1980s, partially reusable SVs have been developed to carry out a multitude of different operations in LEO. This has included the transportation of people, supplies and experiments to and from the International Space Station (ISS), repairing and upgrading the billion dollar Hubble Space Telescope, launching numerous satellites and interplanetary probes as well as conducting scientific experiments in-orbit. The majority of these operations were carried out by a SV fleet of the National Aeronautics and Space Administration's (NASA's) Space Shuttle.

After the final flight of the Space Shuttle in 2011, the development of a new autonomous reusable SV to partially replace it has been discussed globally. However before a single nation or agency can justify investing a large amount of money in a SV programme, the benefits and potential market opportunities must be studied and fully understood.

Although not considered to be an exhaustive list, this section briefly discusses four reasons as to why autonomous, reusable SVs are critical to future LEO operations, used as either:

- A low cost technology demonstrator platform to close the development funding gap
- An orbital microgravity research laboratory free from human interference
- A way to clean up space debris from our critical LEO region
- An in-orbit repair capability which fundamentally changes the way we operate satellites

A Low Cost Technology Demonstrator Platform

During the development of a new product for space there are often two primary sources of funding available to bring the idea from a first concept up to a fully qualified design:

- The first source is typically used to fund preliminary studies and early prototypes to prove the feasibility of technological concepts. This source of funding aims at encouraging new ideas and innovation.
- The second source typically becomes available once the technology is better understood and largely de-risked. To receive funding it is usually important that the route to selling the component or services for a profit is clear (i.e. it is a low risk investment for industry).

At some point when advancing a concept it is usually necessary to test prototype hardware in operational conditions to both assess performance for future development and raise the Technology Readiness Level (TRL) of the product. The cost of doing this is very high for space hardware for two reasons:

- Launch costs are very high. The example costs for the Atlas family of LVs given in Figure 1 show that reaching Geostationary Transfer Orbit (GTO) can require $15K to $30K per kg [1].
- It is unlikely that any prototype needed to be tested will operate independently in orbit. Therefore it is necessary to either develop a dedicated satellite platform to test the hardware or pay a platform operator to "piggyback" on an existing mission. The former is very expensive and requires considerable engineering design and manufacturing effort. Although a much cheaper option, the latter can still prove costly but most importantly it can often take an unacceptably long time to identify a willing and able platform operator.

For both of these reasons full product development, including the testing of a prototype in operational conditions, usually needs more investment than can be provided by University grants or IRAD. However at the point when the largest funding is needed, the product is often not yet considered to be mature enough for direct industrial investment.

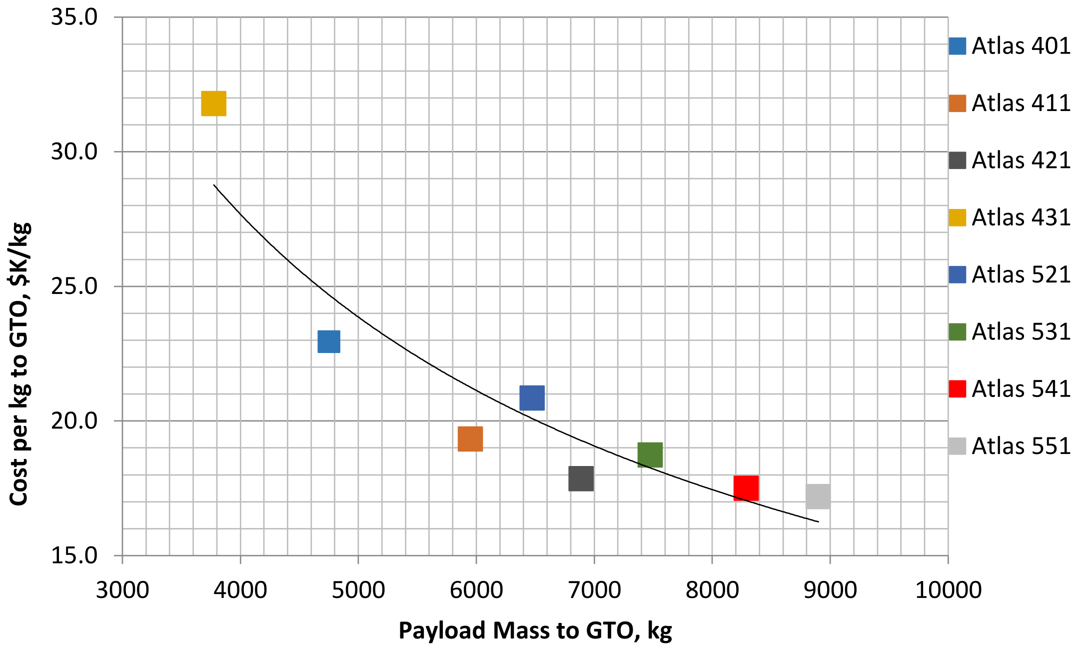


Figure 1 – Launch vehicle costs per kg to deliver payloads to GTO [1]

As is shown in Figure 2, this can create a "Valley of Death" funding gap where the development of many products is forced to cease. An autonomous, reusable SV could be used to reduce this funding gap because system reusability has the potential of reducing the cost of launch per kg considerably. A fleet of SV operating regular flights would also provide a dependable platform service to mount any prototype hardware. Another added benefit is that a reusable SV would be able to return any tested hardware back to Earth for refurbishment or further testing.

This cost reduction and readily available capability could be crucial in encouraging the development of new products and technologies for space.

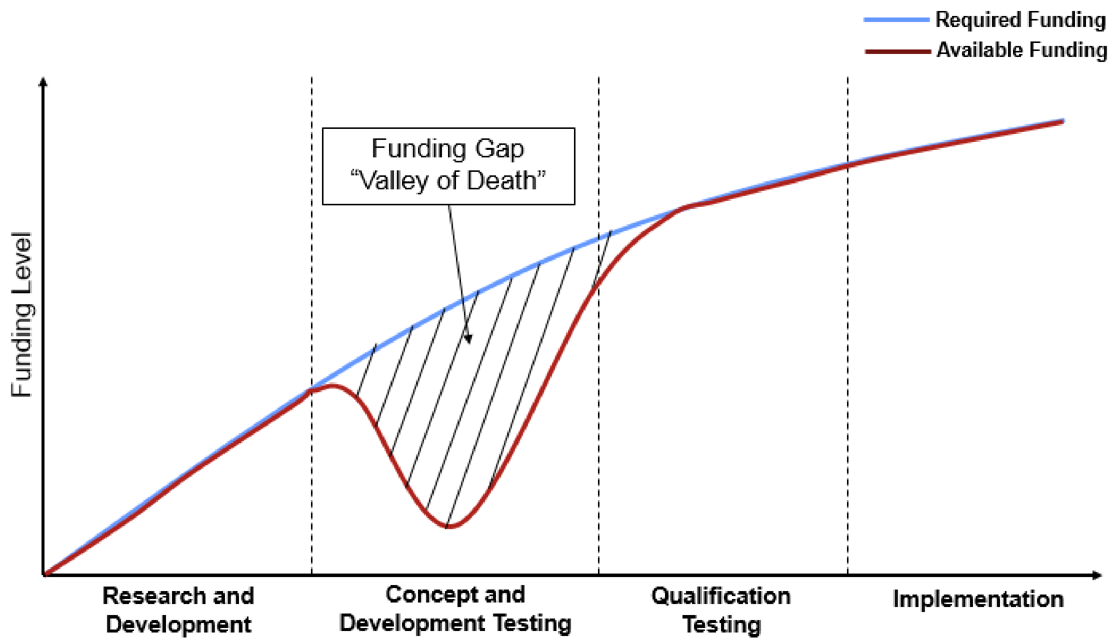


Figure 2 – The required funding and available funding for product development

An Orbital Microgravity Research Laboratory

The popularity of microgravity research has increased steadily since the mid 1980's. This is evident from the 30 year growth trend of microgravity patents, as shown in Figure 3 [2]. Currently this research is mainly performed on the ISS, which is not an ideal platform due to human presence influencing experimentation. Furthermore, the ISS is scheduled to cease operations in 2024 with a potential extension to 2028 [3]. A newly developed autonomous SV could fill the gap in the market left by the ISS with improved platform capability.

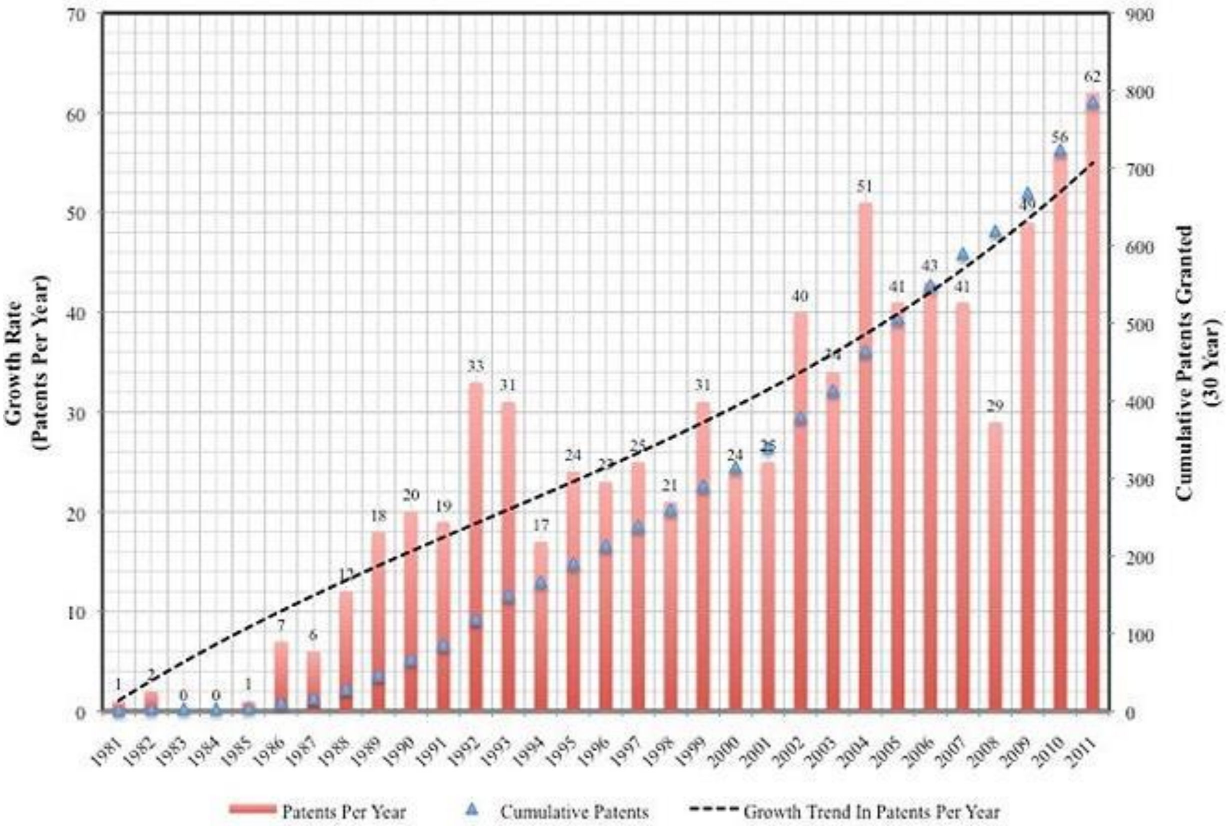


Figure 3 – Microgravity-Related Patents: 30 Year Growth Trent – Credit: NASA [2]

This important and growing area of space research is particularly applicable to preparing humanity for spaceflight and extra-terrestrial exploration. Before venturing away from the safety of Earth it is important to understand how the low gravity of space effects our bodies. Key areas of interest are; bone development, healing of wounds and sensory response. It has also been observed that microbes such as Salmonella become more virulent in microgravity, meaning there was an increase in its infection potential, adding further considerations to human space exploration [4].

Microgravity research has also yielded important terrestrial advances, particularly in the field of pharmacology. Observing how bones develop and change in microgravity has led to advances in the understanding of osteoporosis [5]. NASA experiments aboard the space shuttle have studied the growth of microbes to help treat fungal rashes and infections suffered by young children [6]. Understanding microgravity is therefore very important, not just with respect to human space travel, but also for medical research.

It should also be noted that the advantage of using a re-usable SV over a conventional satellite to carry out experiments is that it is possible to retrieve experiments once the SV has safely returned them back to Earth.

A Way to Clean Up Space Debris

Space debris has become an ever increasing problem in LEO and further collisions threaten to cause a chain reaction event destroying all satellites in this region and make it unusable for future missions. The sensible fear of this chaotic scenario has led to the creation of international space laws under the United Nations (UN) Committee on the Peaceful Uses of Outer Space (COPUOS) and even inspired the 2013 science-fiction film Gravity [7].

As the space debris growth trend shows in Figure 4, the problem has been considerably exacerbated over the last decades due to two major events:

- China testing an anti-satellite weapon against a weather satellite in 2007
- The collision of the Cosmos 2251 and Iridium 33 satellites in 2009

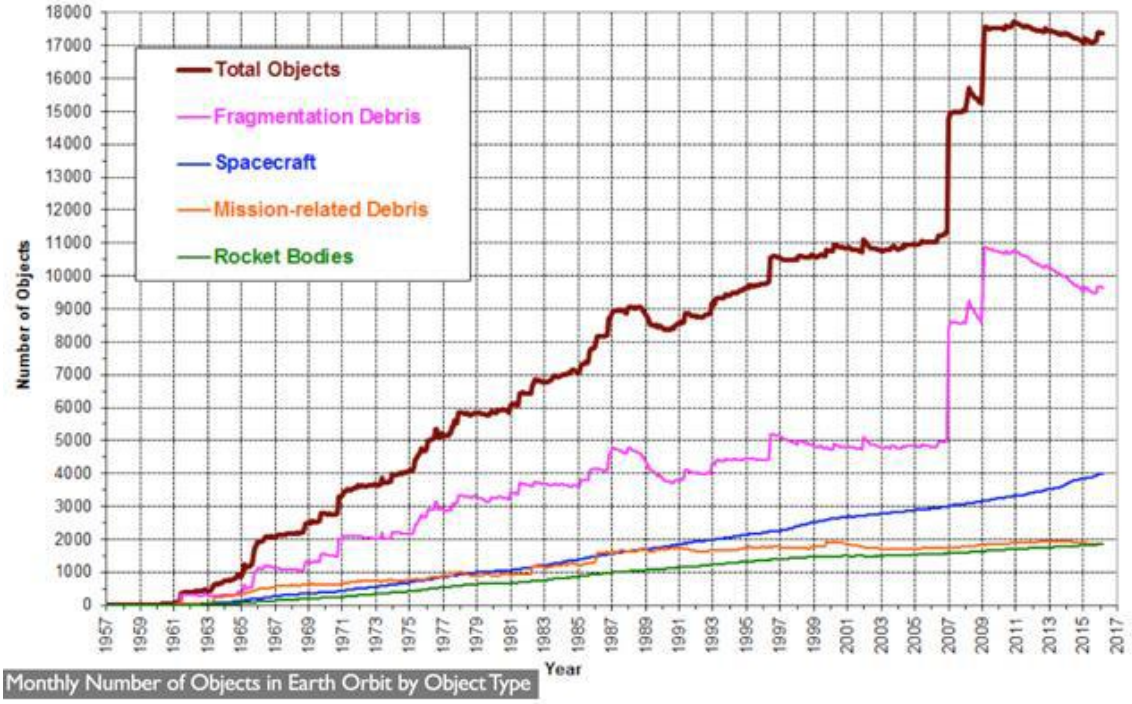


Figure 4 – Monthly Number of Objects in Earth Orbit by Object Type - Credit: NATO [8]

The graph in Figure 4 shows almost 20,000 objects that are typically >10cm in diameter, which are officially catalogued by the United States Space Surveillance Network. However much smaller (and far more numerous) objects are capable of causing significant damage. For example, whilst on the ISS ESA astronaut Tim Peak observed a 7mm circular chip on one of the station's windows, shown in Figure 5 [9]. ESA reported that this was possibly caused by a paint flake, no bigger than a few thousandths of a millimetre across. With more than 170 million objects >1mm estimated to be currently in orbit, space debris is a problem that the international community must urgently act upon [10].

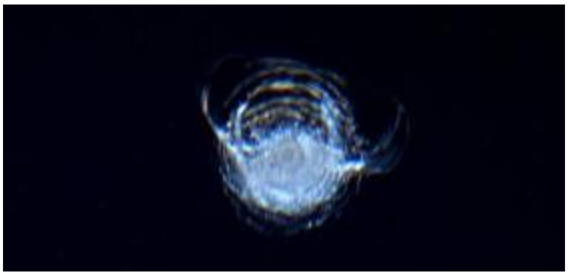


Figure 5 – ISS impact chip due to space debris – Credit: ESA [9]

Multiple methods for removing space debris from the critical LEO region have been conceptualised. These methods either act to de-orbit the debris until it re-enters and burns up in the Earth's atmosphere or raise the debris orbit until it is no longer in the critical region. Methods range from robotic arms and harpoons to physically grabbing the debris to contactless ion beam shepherding, shown in Figure 6, where a spacecraft using the exhaust of the engine to decelerate the object until it re-enters the atmosphere [11].

Figure 6 – Ion engine shepherding – Credit: ESA

An autonomous SV would be well suited in using these methods to clean up the LEO region. It could rendezvous and deal with multiple debris objects during a single mission. Through an intensive campaign over several years, a reusable SV could make a considerable impact to cleaning up the LEO region.

A Satellite Repair Capability

The high cost of building and launching satellites usually means that they are engineered with large safety factors and high levels of redundancy. This redundancy requirement is catered for by having back-up components within a satellite or by having additional satellites within a constellation offering system level redundancy. However despite best practices it is not always possible to anticipate all failure modes, especially for one-off science missions. Typically once a satellite has been launched there is no chance to repair anything that does go wrong.

For a fraction of the total mission cost, an operator could commission a SV to rendezvous with a satellite and repair any malfunctioning equipment as required. The prime example of this type of service was carried out on the $1.5 billion Hubble Space Telescope [12]. Due to a malfunction of a measuring device during manufacture, the edges of Hubble's main mirror were polished slightly too flat, leaving the telescope unable to focus perfectly. Over Hubble's lifetime a total of five upgrade and repair missions were carried out by the Space Shuttle. The difference in imaging before and after the 1993 servicing of Hubble is shown in Figure 7.

Figure 7 – Hubble Space Telescope imaging before and after servicing – Credit: NASA [13]

With the shuttle no longer operating, there is a potential market for an autonomous SV to offer a reactive repair and upgrade services for satellites. The SV could also be commissioned to extend the on-orbit lifetime of expensive satellites by replacing degraded power subsystems. To achieve this objective, it is important that any developed SV maintains a high level of mission flexibility.

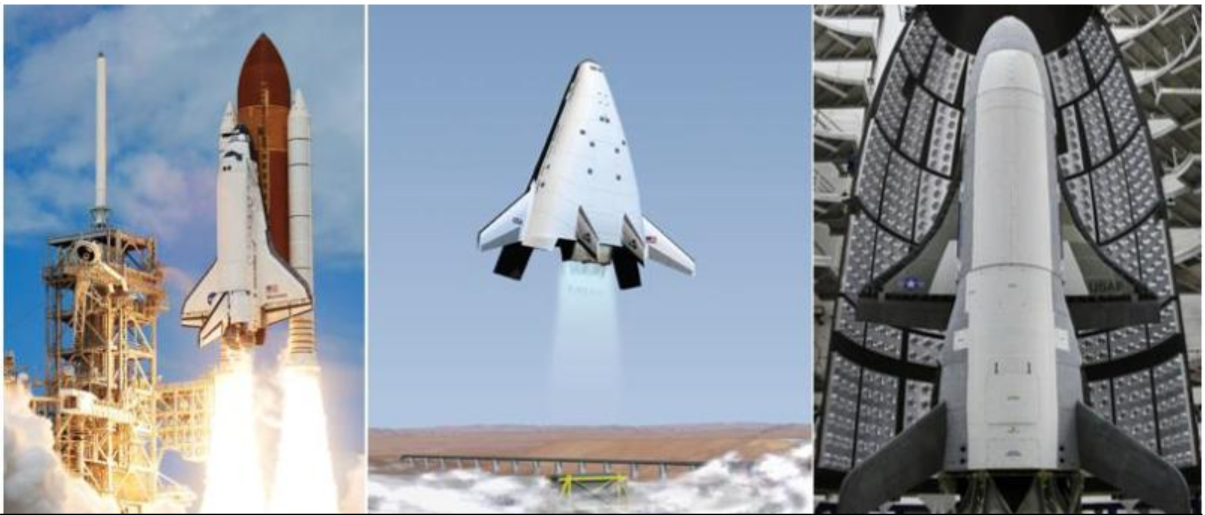
Overview of Space Vehicles Past and Present

The previous section outlined some key areas where a SV may be used as either:

- A low cost technology demonstrator platform to close the development funding gap
- An orbital microgravity research laboratory free from human interference
- A way to clean up space debris from our critical LEO region
- An in-orbit repair capability which fundamentally changes the way we operate satellites

Despite these promising market place opportunities, before an agency or space fairing nation commits to developing their own autonomous, reusable SV, it is sensible to examine what has been developed in the past and what is planned for the near and long term future.

The United States has led the way with SV development over the years, most notably with NASA's Space Shuttle, shown in Figure 8. Since its first flight in 1981 until 2011, the vehicle (costing a total of $210 billion) has greatly furthered SV technology and concepts of operations [14]. Over its 135 launches its missions have included servicing the ISS, sending scientific satellites on interplanetary trajectories and acting as a "Spacelab" for vital experimentation. The LEO payload carrying capability of the shuttle was an impressive 27,500kg but this was the primary driver of the high costs per launch of $450 million [14].



Space Shuttle, Credit: NASA	X-33, Credit: NASA	X-37B, Credit: USAF

Figure 8 – United States heritage in Space Vehicle Design [14], [15], [16]

With a view to offering an alternative to the high launch costs of the Space Shuttle, the United States also invested $1B in the partial development of a reusable Single-Stage-To-Orbit (SSTO) SV known as the X-33, shown in Figure 8 [15]. This contract was carried out by Lockheed Martin "Skunk Works" and aimed to bring down the cost of launch by an order of magnitude. Unfortunately the programme was cancelled in 2001 due to termination of government support and a reduction in the industries appetite to bring large, multi-tonne payloads to LEO.

In general over the past two decades the space community has begun to move away from the practice of putting a multitude of scientific payloads and experiments on board large, satellites such as ESA's Envisat Earth observation satellite. Instead payloads are now typically divided and placed onto several small satellites. This prevents a single point of failure and also allows the mission architect to optimise the orbit of each satellite for its particular payload, rather than having to use a compromise orbit to achieve several objectives. Although there are exceptions where simultaneous observations using different instruments is required, this trend has been aptly named the "Small Sat Revolution".

The development of modern SVs has had to keep step with this revolution and so development has shifted towards launching smaller payloads. This in-part has shaped the United States latest SV venture shown in Figure 8, the X-37. It is the smallest and lightest SV flown to date with a launch mass of around 5,000kg (less than a quarter of the Space Shuttle's payload capacity) [16]. It is currently operated by the United States Air Force (USAF).

Buran	Shenlong

Figure 9 – Russian Buran and Chinese Shenlong space vehicles

Russia and China have also developed their own SV capabilities in the form of the Buran and Shenlong SVs respectively, shown in Figure 9. Developed in the same decade as the Space Shuttle, the Buran had a similarly large payload capability of 30,000kg [17]. It was arguably superior to the Space Shuttle but only flew once due to the Russian economic crisis of the 1990s and the breakup of the Soviet Union. It was destroyed in 2002 when the hangar it was kept in collapsed. The much smaller Shenlong SV (launch mass between 5,000kg and 10,000kg) began suborbital testing in 2011. Although not confirmed the SV could be being developed to serve the Tiangong 3 space station due to completed no later than 2022 [18].

The development of future SV is no longer the sole arena of national and international space agencies. Private companies have been working now for several years to develop SVs for commercial use. The focus of most of these companies is to significantly reduce launch costs and some are building SVs to develop a new age of space tourism industry. The most notable examples of these private ventures are shown in Figure 10.

SpaceShipTwo, Credit: Virgin Galactic	Skylon Credit: Reaction Engines Limited	XCOR Lynx Credit: XCOR Aerospace

Figure 10 – Commercially developed space vehicles

European Space Vehicle Development

Unlike the United States, Russia and China, ESA historically have not focused on the development of SV technology. Over the years this has led to a critical knowledge gap that must be addressed to ensure that Europe does not fall behind other major space fairing nations. In response to this issue, ESA commissioned the development of the PRIDE IXV, shown in Figure 11. The rational was that this experimental suborbital SV would act as a demonstrator to prove key enabling technologies needed for future development.

Figure 11 – PRIDE IXV prior to launch and after splashdown, Credit: ESA [19]

ESA's PRIDE IXV, developed by an Italian led consortium, was launched in February 2015 (launch mass of 1,800kg) by a Vega rocket [19]. It performed one orbit of the globe before re-entering at a speed of 7.5km.s^{-1}. When the air became sufficiently dense the ASCS took over the steering of the SV using two small flaps at the rear of the vehicle. The ASCS controlled the SV from hypersonic speeds, through supersonic speeds and eventually down to subsonic speeds. Once at subsonic speeds a series of parachutes were deployed to slow the SV down further before it successfully splashed down in the water to the west of the Galapagos Islands, as shown in Figure 11. This flight demonstrated ESA's general concept of operations and successfully proved subsystems critical to the development of a reusable, autonomous SV, such as the Thermal Protection System (TPS), the parachute descent system and the hypersonic flight control system.

PRIDE IXV carried out its mission successfully and ESA director general Jean-Jacques Dordain commented that it "Couldn't have gone better." Moving on from this prototype, ESA has opted to develop a fleet of SVs to perform LEO operations. This future SV has been named Space Rider (previously known as the PRIDE Innovative Space Vehicle (ISV)) and aims to be in orbit by 2021. This multi-functioning vehicle, illustrated in Figure 12, will deliver small payloads to LEO and its listed potential uses include; servicing the ISS, performing in-orbit microgravity experimentations, active space debris removal and acting as a low cost in-orbit technology demonstrator.

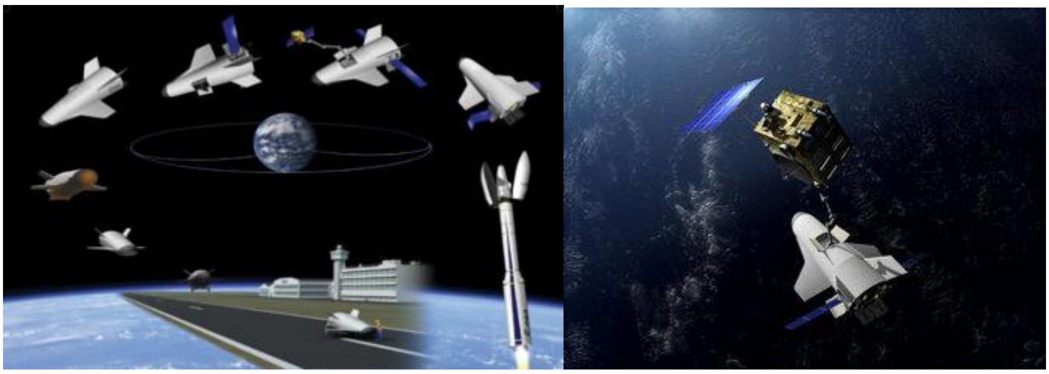


Figure 12 – Space Rider concept of operations, Credit ESA

Developing Space Rider at LMUK Ampthill

The primary subsystems of Space Rider are broadly similar to PRIDE IXV. However, Space Rider will need to perform a soft landing as apposed to splashing down hard in the ocean. This maximises the reusability of system and preserves the integrity of sensitive payloads that are being returned to Earth. After a parachute system, similar to PRIDE IXV, has been deployed Space Rider will then deploy a parafoil. The parafoil is used to steer Space Rider to a desired location where it will either touch down on conventional Landing Gear onto a runway like an aircraft or be captured by a helicopter utilising a MAR system.

LMUK Ampthill are currently funded by ESA to develop the following subsystems as part of the Phase A (Feasibility Study) and the Phase B1 (Preliminary Design Loop) of the Space Rider programme:

1. The ASCS
2. The Landing System using either:
    a. A Conventional Landing Gear system
    b. A MAR system

In the subsequent three sections, each investigated subsystem is discussed in more detail and some key areas of design are presented to give the reader a sense of some of the key decisions that must be made when designing critical SV subsystems.

The ASCS

As stated previously, the primary role of the ASCS is to control the descent of the Space Rider vehicle from hypersonic reentry until control is passed to the parachute descent system. The ASCS consists of the following components as identified in Figure 13:

- An actuator per flap, which creates the force needed to move the flap to a desired angle at a required speed
- A mechanical linkage along which the force from each actuator is transferred to each flap
- The Actuator Control Unit (ACU) which takes position requirements from Space Rider's central On-Board Computer (OBC) and translates them into force-displacement requirements for both actuators
- A battery sufficient to power both actuators and the ACU whilst in use

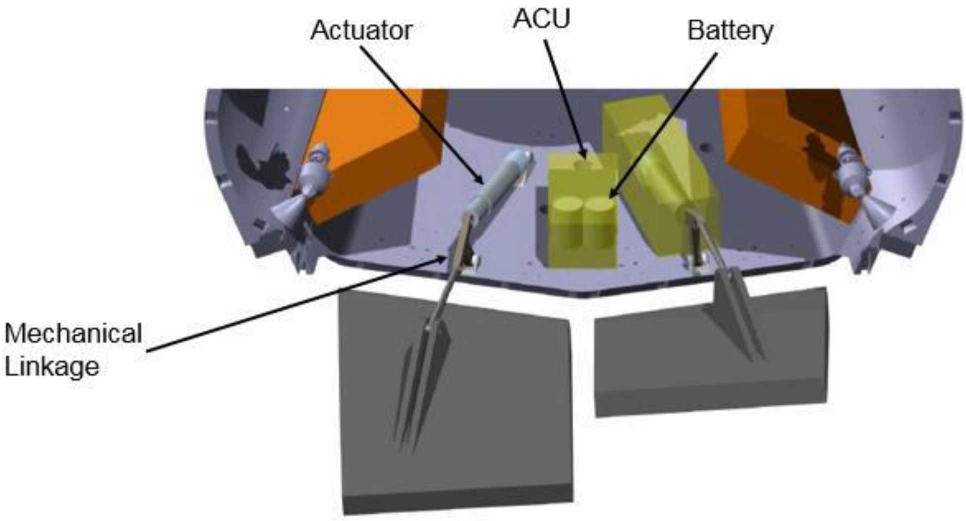


Figure 13 – Components of the ASCS

For the ASCS, one of the primary areas of investigation for LMUK Ampthill was that of the mechanical design linkage. It defines how force is transferred from the actuator to the flap and is a key driver in the specification of hardware.

By creating a mechanical linkage, which maximises the effect of the actuator force on the flap, it is possible to reduce the maximum force requirement for the actuator itself. This generally can mean that smaller actuators can be selected, thus saving mass. As already discussed in relation to Figure 1, mass is particularly important for spacecraft when launch costs per kg are in the order of tens of thousands of dollars. For a reusable SV that launches multiple times, a saving in mass can therefore represent a considerable cost saving over the lifetime of an entire fleet.

In an effort to design an optimised mechanical linkage, LMUK Ampthill created parametric mechanical linkage models within the Mathworks Simscape Multibody environment. Using these models, multiple sensitivity analysis studies were performed to understand the importance of the relative placement and lengths of different sections of the linkage. The output from these studies was the specification for several mechanical linkage design candidates which yielded minimal actuator force requirements. Two of these candidates are shown in Figure 14.

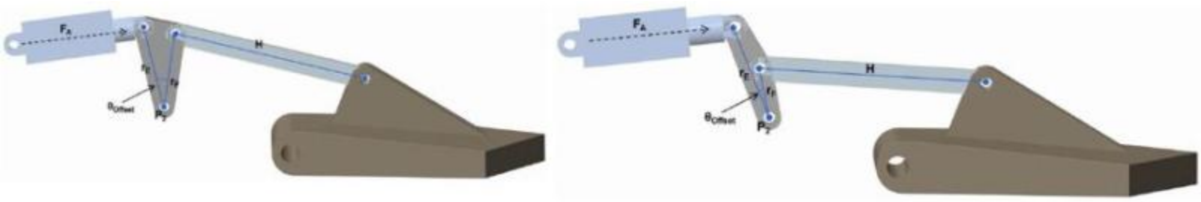


Figure 14 – Candidate mechanical linkage design concepts for the ASCS

Although mass is very important, it is not the only thing that must be considered. The designer must take into account a wide range of considerations when selecting components. In particular the designer must know how components will respond to the space environment, their reliability and their heritage on previous space based applications. These considerations are usually weighted against each other in a trade-off study to select the most suitable equipment. One such trade-off which was carried out for the ASCS was to decide which type of actuator should be used. A decision needed to be made as to whether to utilise either:

- Electro-Mechanical Actuators (EMAs)
- Pneumatic Actuators
- Hydraulic Actuators
- Electro-Hydrostatic Actuators

Pneumatic and hydraulic systems were discounted because of their relative complexity (requiring a system of pumps, pipes, fluid tanks, and regulator valves). It was also recognised that additional design work would need to be carried out to protect these fluid based systems from the thermal and vacuum environments of the mission. Pneumatic actuators may also not be able to provide the fine control requirements needed. Electro-Hydrostatic actuators, although initially believed to be promising, were discounted because there was no space flight heritage of any such system and so their adoption would likely require a lengthy and costly qualification campaign.

Consequently EMAs were downselected for the Space Rider ASCS. These were qualitatively decided to be more mass efficient, reliable and more compatible with the environments experienced by the Space Rider vehicle.

Conventional Landing Gear

The majority of SVs have been designed to use a conventional landing gear, like an aircraft, to safely touch down onto either a runway or a lake bed. For the Space Rider vehicle LMUK Ampthill have been working with a specialist team from Lockheed Martin Aeronautics “Skunk Works” (who worked on the X-33) to perform a preliminary conceptual landing gear design to assess the feasibility. This conceptual design will be traded against the MAR system, discussed in the following section, to decide which is most suitable for the Space Rider vehicle.

The design of a landing gear is highly iterative and calls upon many disciplines of engineering. What follows is a discussion of some of the notable design drivers and trade-offs for the Space Rider landing gear design:

- As with the ASCS, the mass of the subsystem is a primary driver that should be minimised where possible. The mass allocation for each subsystem is specified by the prime contractor and must be adhered to. As mentioned in the previous section, an increase in a few kg can lead to launch cost increases in tens of thousands of dollars or may reduce operational flexibility.
- Unlike conventional aircraft, Space Rider is not expected to perform a rolling take off from a runway. Therefore instead of using wheels, tyres and a braking system (often referred to collectively as the rolling stock components) it is possible for the Space Rider landing gear to be equipped with skids to bring it to a stop on landing. This has the potential to reduce the mass of the system but also could increase the between flight inspection and refurbishment time. The choice between an aircraft type rolling stock and a skidded system must be carefully traded.
- The shape and mass characteristics of the Space Rider vehicle make landing stability a particularly challenging requirement when designing the landing gear. The gear has to be designed to make sure that the vehicle doesn’t turn over, tip back or scrape its tail upon landing.
- Space vehicles historically have required long distances to stop them due to their high landing speeds. Space Rider would make a controlled parafoil descent to a runway and as such the landing speeds are far less than say the Space Shuttle. Nevertheless, stopping distance is a key requirement for the landing gear that must be fed up to the prime at system and operations level when they are considering potential landing locations.
- The between flight time for Space Rider (months) is far greater than for a conventional aircraft which may need to take off again in a matter of hours. Therefore it is possible to consider the use of crushable core systems, as used for the Apollo lunar landers shown in Figure 15, in place of conventional shock absorbers. This represents a potential mass saving but will increase the refurbishment time of the vehicle.

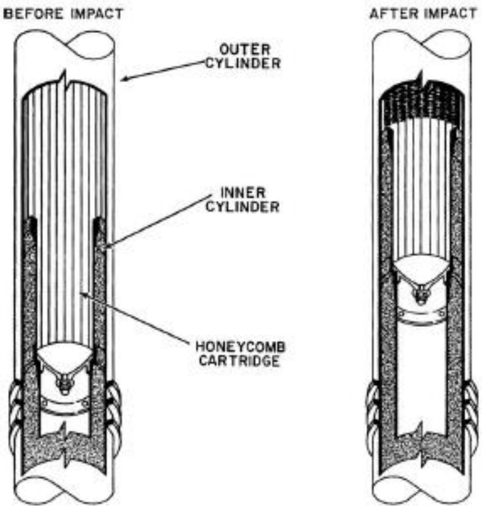


Figure 15 – Apollo Lunar Lander crushable core landing gear components

The MAR System

The broad advantage of using a MAR system over a conventional Landing Gear system is that the vehicle can save 100s of kg by effectively externalising its landing system (i.e. rather than use on-board Landing Gear it will use a helicopter and a grapple system).

MAR systems have been developed for many different purposes over the last 50 years, including the retrieval of Unmanned Air Vehicles (UAVs) and air-launched cruise missiles. For each of these applications, all MAR systems rely on three key operations:

a) the retrievable payload deploying a means of capturing it, e.g. by deploying a parachute or parafoil that can be grabbed in some fashion
b) the retrieving aircraft rendezvousing with the retrievable payload
c) the retrieving aircraft capturing the retrievable payload

Lockheed Martin Space Systems Corporation (LMSSC) have developed MAR systems since the 1960s and to date have worked through three primary generations of design. The first generation of MAR systems, shown in Figure 16, utilised multiple engagement hooks attached to retractable booms below aircraft to rendezvous with and capture a payload floating below a deployed round parachute. The aircraft was required to pass close enough to the descending parachute to drag the boom through the parachute and snag a reinforced network within the canopy. The hooks were connected to a bespoke constant-tension winch that decreased loads and oscillation between the aircraft and payload by paying out line at a pre-set tension, generally about 1.25 times the weight of the payload. This system of MAR is known as a Hook-Boom-Winch (HBW), system. Due to the round parachute’s static nature, it had to be captured accurately just as the aircraft flew through the wake of the parachute.

The first generation methodology is described as a near-miss, mid-air collision system. This intersection occurs at very close quarters and with the aircraft travelling at a high speed relative to the parachute (greater than 50m/s (100kts) when using a fixed wing aircraft). The speed and proximity of this intersection makes the rendezvous difficult to achieve, dangerous for the pilot and transfers large forces to the retrievable payload and aircraft. The last known flight test of the first generation MAR system, used to retrieve an air launched cruise missile, was performed at the Utah Test and Training Range in 1989.

Figure 16 – First Generation MAR Capture Using a C119 [20]

The second generation MAR system, shown in Figure 17, was upgraded by Vertigo Inc. in 1991 to use a parafoil system instead of a round parachute as part of a UAV programme. This upgrade allowed the intercepting aircraft to fly in formation with the payload. Parafoils are designed to fly along a relatively straight path, facilitating a more controlled, smoother and safer retrieval than round parachutes which descend in an unstable float. The recovery helicopter takes up a trailing position above and behind the parafoil and overtakes it on a parallel path. As the helicopter flies over the parafoil, it uses a HBW system to snag the parafoil.

Figure 17 – Second Generation MAR Capture with a Tandem Parafoil [20]

The second generation MAR system requires a lower relative intercept velocity of 10m/s (20kts), which makes for a far gentler engagement. Training requirements for the pilot are still considerable but are greatly reduced and in the event of a miss, multiple passes are available. This system was used for the Genesis sample return mission in 2004 where stunt pilots were used to perform the manoeuvre. Although highly successful in testing, during the Genesis mission capture its parachute system failed and the second generation MAR system was not given the chance to demonstrate its effectiveness in operation.

The third generation MAR system, referred to as 3GMAR, improves on the second generation MAR system by eliminating the requirement for a HBW system. Instead, it suspends an Aero-Manoeuvring Grapple (AMG) below the helicopter which engages a capture line trailed behind the parafoil whilst flying in formation (i.e. zero intercept velocity) with the payload. The payload then becomes a suspended load as the helicopter pulls up and the payload weight is transferred to the grapple. This is referred to as a Trailing-Line-Capture (TLC) method, and is illustrated in Figure 18.

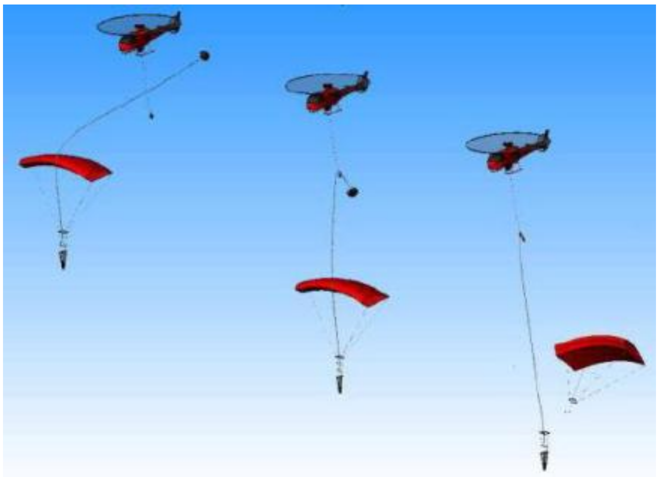


Figure 18 - Third Generation MAR Operation [20]

The TLC method of 3GMAR is considered to be a much safer form of capture than the previous HBW systems as it utilises a formation flying manoeuver as opposed to an overtaking manoeuver. It allows much heavier loads to be captured, now limited by the helicopter performance as opposed to the capability of the HBW system. It is also inherently more reliable than previous generations as the capture is effectively static (i.e. zero intercept velocity) rather than dynamic, allowing capture to be attempted constantly during the parafoil guided section of descent (excluding altitude limits). The reliability is also greater for 3GMAR than previous generations.

Apart from the improved reliability and capability of the system, changing from a HBW system to a TLC method (where an AMG is suspended below the helicopter's standard cargo hook) allows two other critical benefits:

a) Rigging and derigging becomes a much simpler and shorter process. For example, it takes less than an hour to connect the AMG to the helicopter, compared to installing the HBW system, which for the Genesis mission was an 8-12 hour task for a 4-6 man team. This helps to minimise costs during setup

b) It is not necessary to re-certify the aircraft. Installing a HBW system changes the external aerodynamic configuration of the aircraft, which invalidates the aircraft type certificate. Dealing with this requires extensive coordination with the Federal Aviation Administration (FAA) in the U.S. or similar agency in other countries. There are various strategies that can be implemented to tackle this: experimental classification; a Part 337 waiver; or Supplemental Type Certificate (in order of increasing expense). The TLC configuration requires no such authorisation, as it is operated within the requirements of Federal Air Regulation, Part 133, Suspended Payloads and is similar in other countries.

The main aspects of using the 3GMAR system on the Space Rider vehicle are illustrated in Figure 19.

Figure 19 – MAR system concept of operations for the Space Rider vehicle

Trading-Off MAR and Landing Gear

The final task for LMUK Ampthill during the Phase A design phase was to trade-off conventional landing gear and the MAR system against customer driven figures of merit. This trade was then presented to ESA and the prime contractors for their consideration such that they could downselect a preferred landing subsystem for the following Phase of study.

The use of landing gear was noted to have better flight heritage, having been proven on other SVs. However, a landing gear for Space Rider would have far greater mass than the equivalent MAR system, cost more to develop and is thought to have a longer design and development schedule.

The MAR subsystem on the other hand represents a relatively large mass saving of between 150kg and 180kg. For a fleet of 3 to 4 SVs flying 2 to 3 times a year over a lifetime of 5 years, choosing MAR over landing gear yields an estimated cost saving of between $110M and $320M (using the cost per kg data shown in Figure 1).

Although MAR it is not flight proven for SVs, it is already under development and well tested. If Space Rider was to use a MAR system, it would simplify other subsystems such as the TPS which would no longer have to accommodate landing gear bay doors and the required sealing for reentry.

A disadvantage of a MAR subsystem is the higher perceived risks: the idea of catching an SV out of mid-air with a helicopter seems unnecessarily risky compared to a more conventional landing gear. However with each successful test of the 3GMAR system and engagement with key customer stakeholders present, this perceived risk is being greatly reduced.

The Near Future of Space Rider

This paper has discussed through some key motivations for creating a SV, an overview of the current SV marketplace and a brief description of work done thus far by LMUK Ampthill on the Space Rider programme. This work fed into, and has led to, the successful completion of the Preliminary Requirements Review (PRR) conducted between the prime contractors and ESA with inputs from each subsystem.

In the near future, LMUK Ampthill will further develop the ASCS and landing system for the Space Rider programme during Phase B1, known as the preliminary design iteration, which will bring the programme up to the System Requirements Review (SRR).

As for the longer term future of the programme, ESA's ministerial council have announced that they will develop the Space Rider vehicle further through additional phases as it is perceived to be key to future exploration missions. The Space Rider vehicle could then be used to perform the key functions discussed in previous sections:

- Close the development funding gap as a low cost technology demonstrator platform
- Act as an orbital microgravity research laboratory free from human interference
- Clean up space debris from our critical LEO region
- Offer an in-orbit repair capability to fundamentally change the way we operate satellites

It is hoped that this development will give ESA an autonomous and reusable SV capability to bring it in line with other major space fairing entities throughout the world.

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